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Cat's eye quantum well modulating retro-reflectors for free-space optical communications

W.S. Rabinovich[*a], P.G. Goetz[a], R. Mahon[b], E. Waluschka[c], D.S. Katzer[a], S.C. Binari[a], Mark L. Biermann[d] and G. C. Gilbreath[a]
[a]US Naval Research Laboratory, 4555 Overlook Ave., Washington, DC 20375
[b] Jaycor/Titan, 1410 Spring Hill Road, McLean VA 22102
[c]NASA Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

Modulating retro-reflectors (MRR) couple passive optical retro-reflectors with electro-optic modulators to allow free-space optical communication with a laser and pointing/acquisition/tracking system required on only one end of the link. In operation a conventional free space optical communications terminal, the interrogator, is used on one end of the link to illuminate the MRR on the other end of the link with a cw beam. The MRR imposes a modulation on the interrogating beam and passively retro-reflects it back to the interrogator. These types of systems are attractive for asymmetric communication links for which one end of the link cannot afford the weight, power or expense of a conventional free-space optical communication terminal. Recently, MRR using multiple quantum well (MQW) modulators have been demonstrated using a large area MQW placed in front of the aperture of a corner-cube.

For the MQW MRR, the maximum modulation can range into the gigahertz, limited only by the RC time constant of the device. This limitation, however, is a serious one. The optical aperture of an MRR cannot be too small or the amount of light retro-reflected will be insufficient to close the link. For typical corner-cube MQW MRR devices the modulator has a diameter between 0.5-1 cm and maximum modulation rates less than 10 Mbps. In this paper we describe a new kind of MQW MRR that uses a cat's eye retro-reflector with the MQW in the focal plane of the cat's eye. This system decouples the size of the modulator from the size of the optical aperture and allows much higher data rates. A 40 Mbps device has been demonstrated.

Keywords: Modulating retro-reflector, Retromodulator, Free space optical communication, Quantum well modulator, Cat's eye

1. Introduction

1.1. Modulating retro-reflectors

Modulating retro-reflectors (MRR) couple passive optical retro-reflectors with electro-optic modulators to allow long-range, free-space optical communication with a laser and pointing/acquisition/tracking system required on only one end of the link. In operation a conventional free space optical communications terminal [1], the interrogator, is used on one end of the link to illuminate the MRR on the other end of the link with a cw beam. The MRR imposes a modulation on the interrogating beam and passively retro-reflects it back to the interrogator. These types of systems are attractive for asymmetric communication links for which one end of the link cannot afford the weight, power or expense of a conventional free-space optical communication terminal. The MRR demonstrated to date have used a large area modulator placed in front of the aperture, or as one of the faces, of a corner-cube retro-reflector. MRR based on ferro-electric liquid crystals [2], MEMS devices [3] and multiple quantum well (MQW) electro-absorption modulators [4], [5] have been demonstrated recently

For both the liquid crystal and MEMS devices the maximum modulation rate is set by the intrinsic switching speed of the material, which are tens of KHz and hundreds of KHz respectively. For the MQW

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MRR however, the maximum modulation can range into the gigahertz, limited only by the RC time constant of the device. This limitation, however, is a serious one. The optical aperture of an MRR cannot be too small or the amount of light retro-reflected will be insufficient to close the link. For typical MQW MRR devices the modulator has a diameter between 0.5-1 cm and maximum modulation rates less than 10 MHz. This size device is sufficient to close a link at this rate at ranges over ten kilometers, depending on atmospheric conditions and the interrogator. In this paper we describe a new kind of MQW MRR in which much higher modulation rates can be achieved using small MQW modulators simultaneously with large optical apertures.

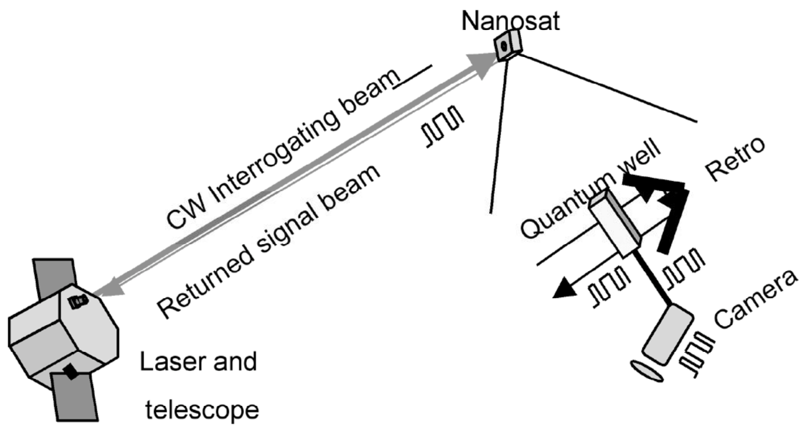

Figure 1. A modulating retro-reflector link

1.2. Scaling rules for modulating retro-reflector links

MRR have different scaling rules than conventional free space optical links. These rules are determined by the fact that an MRR acts simultaneously as a receiver and a transmitter. Thus the larger the MRR aperture the more light from the interrogating beam it captures and the narrower its' return beam divergence is. The optical signal returned by an MRR scales as

$$\frac{P_{laser} \cdot D_{retro}{}^{4} \cdot D_{rec}{}^{2}}{\theta_{div}{}^{2} \cdot R^{4}} \cdot \left[1 - \frac{1}{N_{ext}}\right] e^{-2\alpha_{\mathrm{mod}} L_{\mathrm{mod}}} e^{-2\alpha_{atm} R} \tag{1}$$

where P_{laser} is the power in the interrogating laser, D_{retro} is the optical aperture of the retro-reflector, D_{rec} is the diameter of the interrogator's receive telescope, θ_{div} is the divergence of the outgoing beam from the interrogator, R is the range, N_{ext} is the extinction ratio of the modulator, α_{mod} is the absorption in the modulator , L_{mod} is the thickness of the modulator and α_{atm} is the absorption or scattering loss in the atmosphere. Eq. 1 is in contrast to the scaling relations one would expect for a conventional long-range optical link where the dependence on both aperture and range generally go as second powers.

When atmospheric attenuation is not severe, an MRR link is dominated by the two fourth power relations in (1). The link drops off with range as $1/R^4$. The optical signal, however, increases as the fourth power of the retro-reflector diameter. This obviously motivates using larger retro-reflectors. However for an MQW modulator the capacitance is proportional to the area of the modulator and so the maximum modulation rate scales as

$$1/R_{mod}D_{mod}{}^{2}, \tag{2}$$

where R_{mod} is the sheet resistance and D_{mod} the diameter of the MQW. For a typical MQW modulator capacitances are about 5 nF/cm^2 and sheet resistances vary between 10 and 100 Ohms. Thus the RC modulation limit for an MQW modulator is from 1-20 MHz/cm^2.
This problem can be circumvented by pixellating the modulator into smaller segments and driving those segments with the same signal. This approach however does not reduce the power consumption of the modulator, which scales as

$$D_{mod}^2 V^2 f \qquad (3)$$

where V is the driving voltage for the modulator and f is the modulation rate. This power consumption can become large for high data rates and the heating it induces in the MQW may distort the retro-reflected beam ruining the link.

1.3. Cat's eye modulating retro-reflectors

Given the scaling rules described above there is an obvious problem in achieving long range, high data rate MRR links. These links require high MQW modulation speed, driving one towards smaller modulators, while at the same time requiring a higher retro-reflected optical signal, driving one towards larger optical apertures. This is impossible for a corner-cube based MRR for which the modulator size must equal the optical aperture.

One idea that suggests itself is using a lens to increase the optical aperture. It should then be possible to place the modulator in the focus of the lens and maintain a larger optical aperture and a small modulator aperture simultaneously. However, any optics added to the MRR must have several characteristics, two of which are:

1. An MRR must preserve the retro-reflective properties of the system.

2. An MRR must come as close as possible to maintaining a diffraction limited divergence for the return beam.

A class of optical systems called cat's eye retro-reflectors can provide these characteristics if properly designed. There is no one form of cat's eye retro-reflector, but all contain some sort of focusing optics [6]. A classic form for a cat's eye is shown below in Figure 2.

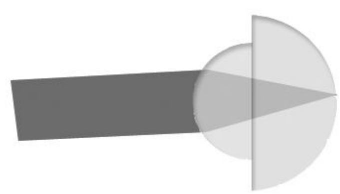

Figure 2. A spherical cat's eye retro-reflector

While this kind of cat's eye has a large field of view (FOV) it also has very large spherical aberration thus violating characteristic 2. This aberration can be avoided by using the optic at high f number (about f/10). This, however, causes other problems and leads to a third cat's eye MRR characteristic:

3. A cats' eye MRR must have as low an f number as possible.

This is because the focal spot of the cat's eye will move as the relative angle between the MRR and the interrogating laser changes. There are several ways to deal with this motion that will be described below, but in all cases it is desirable for the range of possible focal spot positions to be as small as possible. The focal plane size will be proportional to the field of view of the MRR and its focal length. Since we want as large an aperture as possible, we need a low f number to keep the focal length short.

2. Cat's eye optics

2.1. Telecentric cat's eye retro-reflectors

Any cat's eye optic will involve some compromises of desirable characteristics versus cost, size, complexity and weight. A very simple cat's eye optical system uses a telecentric lens coupled to a flat mirror in its focal plane. As shown in figure 3 the telecentric condition assures retro-reflection because, over the effective FOV, a symmetric ray bundle is produced in the focal plane regardless of the input angle of the beam. The flat mirror in the focal plane, when oriented normal to the axis of the lens then inverts the ray bundle so that it retro-reflects.

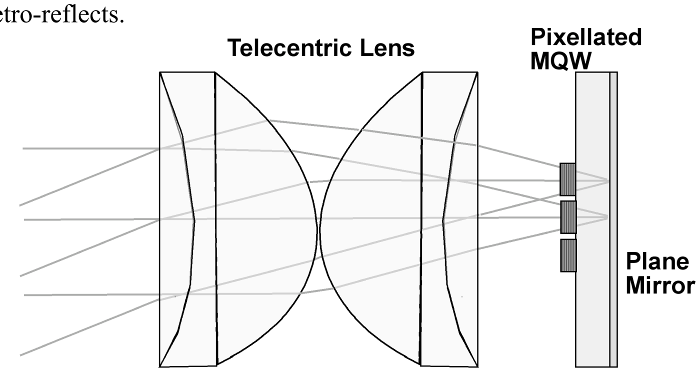

Figure 3. A telecentric cat's eye modulating retro-reflector

This form of cat's eye has several advantages. It is based on telecentric lenses, which are commonly available, and, in addition, it has a flat focal plane. That means that the mirror can be made by coating the back surface of an MQW modulator with metal making integration simple.

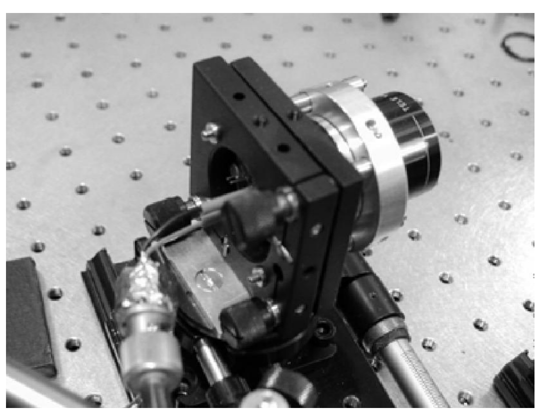

Figure 4. Prototype telecentric cat's eye modulating retro-reflector

We constructed a telecentric cat's eye MRR using a 1 cm aperture Plossl objective. A photograph of the device is shown in figure 4. We measured the optical FOV of the telecentric cat's eye in our laboratory. The optical FOV is a measure of the optical power that is retro-reflected as a function of the incident angle of the light into the cat's eye. The optical FOV of the cat's eye depends on any vignetting in the cat's eye and distortions in the retro-reflected beam that increase its divergence, decreasing the power returned to the interrogator. For short ranges where the retro-reflected beam is smaller than the receive optics of the interrogator only the vignetting matters, but for longer ranges both these effects must be convolved. Figure 5 shows the vignetting and combined vignetting and distortion loss measured for the cat's eye as a function of angle. For a short-range link the MRR has a half power FOV of about 30 degrees, while for longer range, where the combined curve is used, the FOV is about 20 degrees.

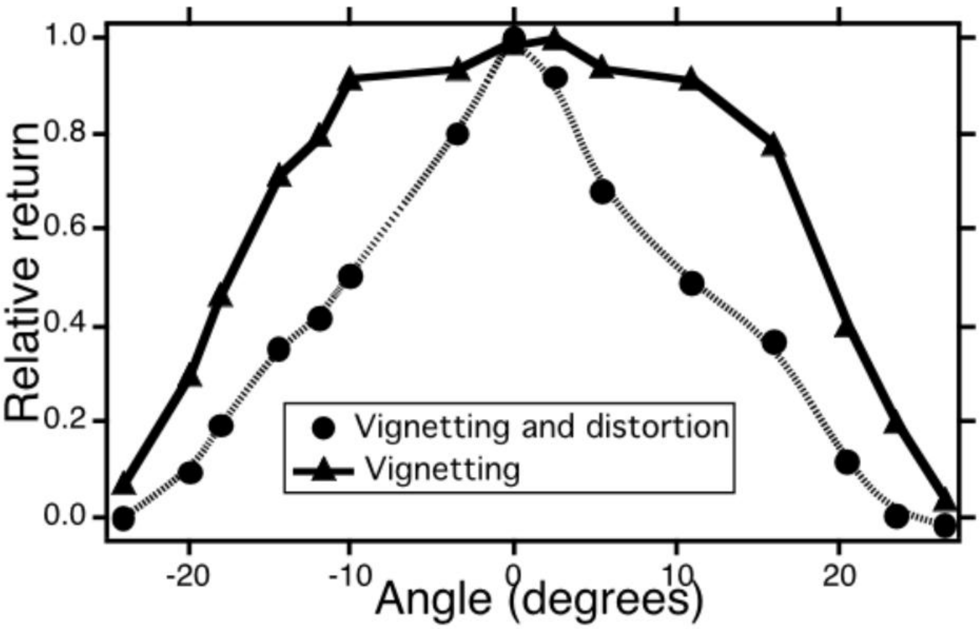

Figure 5. Relative return of the cat's eye retro-reflector as a function of incident angle considering the effects of both vignetting and combined vignetting and distortion.

While simple, this cat's eye optic is not optimal with respect to the desired characteristics. It is about an f/4 optic and as a result the focal spot moves about 1 mm for every 2.5° change in incident angle. Covering the entire 30° FOV thus requires a focal plane that is 1.2 cm in diameter. In addition the retro-reflected return is 4 times diffraction-limited at normal incidence resulting in a 12 dB loss over diffraction limited optic. Despite these limitations telecentric cat's eyes are quite attractive for many applications.

2.2. Aspheric diffraction limited cat's eye retro-reflector

When optimum performance for a cats' eye MRR is desired a custom optic must be designed. There are many different sorts of designs that are possible each emphasizing different metrics. We developed a lens based on catadioptric[7] design optimized for wavelengths around 1 μm.

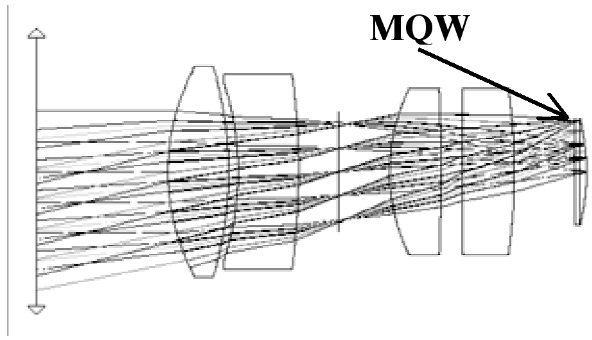

Figure 6. Ray trace of the diffraction limited cat's eye.

The objective consists of four refracting elements. The first surface of the first refracting element is parabolic, all other surfaces are spherical. The aperture stop is between the second and third elements, and the secondary mirror acts as the field stop in the system. When used as an MRR, a transmissive modulator inserted just in front of the secondary mirror would serve as the field stop. Unlike the telecentric cat's eye described above this optic uses a curved reflector. In this case then the MQW must be transmissive and placed in front of the back mirror.

A ray trace of the optic is shown in figure 6. It provides diffraction limited return over a 30 degree FOV with little vignetting. The effective f number of the system is f/2. The focal plane size necessary to cover the entire FOV is about 1.4 cm. While the system is not telecentric, the combination of the refractive elements and the curved reflector produce a system that is in effect locally telecentric.

We fabricated this optic including a housing with space for focal plane circuitry. A photograph of the diffraction limited cat's eye MRR is shown in figure 7.

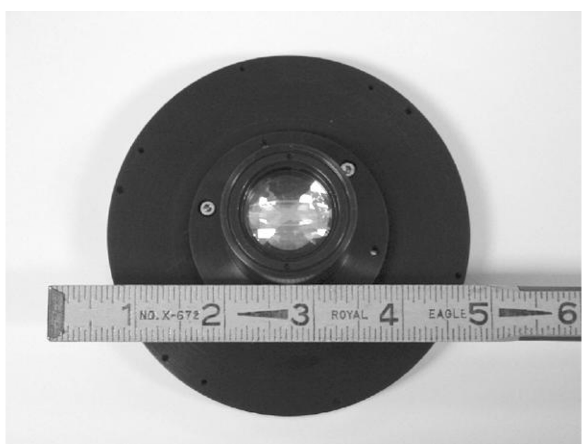

Figure 7. Fabricated diffraction limited cat's eye optic and circuitry housing

The performance of the cat's eye was evaluated using an optical interferometer. A flat wavefront was sent into the optic and an interferogram of the retro-reflected beam was recorder as a function of incident angle. Over the full FOV the retro-reflected wavefront was undistorted, indicating diffraction limited performance. Interferograms at normal incidence and 6 degrees off normal incidence are shown in figure 8.

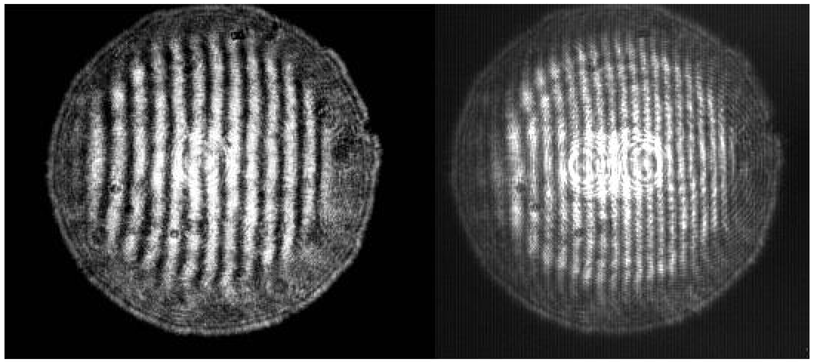

Figure 8. Optical interferograms of the cat's eye optic at various angles of incidence

3. Multiple quantum well focal plane

3.1. Multiple quantum well modulators

Multiple quantum well electroabsorption modulators consist of a PIN diode in which alternating, very thin, layers of two semiconductor materials, a well and a barrier, are grown into the intrinsic region. An electric field is applied by placing a reverse bias voltage on the diode. This field changes the absorption of the MQW in a range of wavelengths around the bandgap of the well material. The bandwidth of the electroabsorption is on the order of 10 nm, but the particular wavelength of operation can be selected by the choice of the well material. These kinds of modulators are insensitive to angle of incidence or polarization, which is a very important property for MRR systems. Typical optical contrast ratios for these sorts of devices are between 2:1 and 3:1 and typical drive voltages are between 15-20 V across a 1.5 micron thick intrinsic region.

For use in MRRs we have investigated MQW electroabsorption modulators based on InGaAs wells with either AlGaAs or InAlAs barriers grown on either GaAs [5] or InP. These material systems allow us to cover two wavelength bands of operation: one between 0.85-1.06 μm and another in the 1.55 μm telecommunications band. The latter has the advantage of being eye-safe.

3.2. Limited field of view MQW focal planes

While a cat's eye optic does produce a small optical spot in the focal plane, the position of that spot varies with the angle of incidence. For a corner cube MRR the MQW size and optical aperture are equal. For a cat's eye MRR the MQW size is coupled to the optical aperture and the field of view. This is not necessarily advantageous. To cover the entire FOV of the 1 cm telecentric cat's eye optic described in section 2.1 the MQW size must be 1.2 cm; larger than the optical aperture. For the 1.6 cm diameter diffraction limited cat's eye the MQW must be 1.4 cm to cover the entire FOV. In both these cases the use of a cat's eye MRR with a single element MQW modulator provides little or no advantage over a corner cube MRR.

However, for many applications a more limited FOV can be useful. For example, for building to building free space optical communication building sway is less than 1 degree. In this case a cat's eye MRR with an MQW focal plane of less than 500 microns could cover the entire FOV. Such a system could provide very narrow divergence retro-reflected beams (on the order of 150 microradians) without the need for any active pointing.

Other applications can require a discontinuous wide FOV. We have examined the use cat's eye MRR for short-range free space optical interconnects for spacecraft LANs[8]. In such a case several narrow fields of view are distributed over a total FOV that may approach 30 degrees or more. A sparse array of small MQW modulators can be used for such an application.

We demonstrated a sparse array cat's eye MRR based on the telecentric cat's eye. The array consisted of three 1 mm diameter MQW pixels with a center-to-center separation of 2.5 mm. The array thus covered a discontinuous FOV of 12.5° x 2.5° with a field of view of 2.5° x 2.5° for each pixel. The MQW used consisted of 75 periods of 8.5 nm $In_{0.17}Ga_{0.83}As$ wells separated by 3.4 nm $Al_{0.13}Ga_{0.87}As$ barriers. It was grown via molecular beam epitaxy on a GaAs substrate. The exciton resonance for this structure falls at 980 nm, a wavelength at which the GaAs substrate is transparent. This allowed us to place the MQW in front of a flat mirror. Alternatively we could deposit a reflective coating on the wafer itself. A photograph of the cat's eye focal plane is shown in figure 9.

Figure 9. Discontinuous field of view MQW focal plane

The MQW pixels had a 3 dB modulation frequency of 25 MHz and could support data rates of 40 Mbps, much higher than would be possible with a 1 cm diameter corner cube MRR. In addition the cat's eye MRR drew much less power than a corner cube MRR would even if it could be modulated at these rates. If all 3 pixels in the modulator array are driven in parallel with the same signal the cat's eye MRR draws 30 milliwatts of electrical power at 10 Mbps and 120 milliwatts at 40 Mbps. An equivalent corner-cube modulator, pixellated to allow these data rates, would draw 0.25 Watts at 10 Mbps and 1 Watt at 40 Mbps.

3.3. Switched-pixel MQW focal planes

In some cases, such as when one end of the link is mobile, a limited FOV focal plane may not be possible. In this case other approaches must be adopted to effectively make use of the advantages of cat's eye optics. When the entire focal plane of the cat's eye optic must be filled the MQW can be pixellated into an array. In this case only the pixel illuminated by the focal spot of the incoming beam need be driven with the modulation signal. This allows us to maintain a large optical aperture and small modulator size simultaneously.

Some decision circuitry must be used to switch the modulation signal to the appropriate pixel. For platforms where the positions of both ends of the link and the orientation of the cat's eye optic are reasonably well known, for example an inter-satellite optical link, the pixel switching can be directly controlled by a microprocessor. The positional awareness need not be very precise since an individual cat's eye pixel can have an FOV on the order of a degree. Thus such programmed switched-pixel devices may be relatively simple to operate.

In cases in which such positional awareness is not available, it is possible to use the cat's eye array itself to determine the illuminated pixel. An autonomous switched-pixel device can be made by recognizing that an MQW modulator is a PIN diode. It can also be used as a photodetector by applying a constant reverse bias and monitoring the photocurrent. This self-sensing capability can be used either in combination with a microprocessor or directly with an on-chip optically controlled switch to direct the modulation signal to the appropriate, illuminated, pixel.

We are currently working on implementing both forms of switched pixel cat's eye MRRs

3.4. Alternative MQW modulator designs

One of the objectives of cat's eye MRRs is to increase MQW modulation rates to hundreds of Mbps. At these rates the typical MQW drive voltages of about 15 V become harder to produce, so lower drive voltages are desirable. In general there are two ways to reduce drive voltage while maintaining optical contrast ratio, one can alter the MQW electroabsorption directly through more complex bandgap engineering or one can alter the optical properties of the MQW through asymmetric Fabry-Perot structures. For a cat's eye MRR using an asymmetric Fabry-Perot structures can be difficult because an optimal cat's eye optic will have a low f number and hence the ray bundle at the focus will have a large cone angle. This will reduce optical contrast because asymmetric Fabry-Perot modulators have a strong angular sensitivity.

We have examined bandgap engineering as an approach to reducing drive voltage. Our previous InGaAs modulators have been based on simple square wells. Symmetric coupled wells have been shown to reduce MQW drive voltage in a variety of material systems[9]. We designed and fabricated a strained InGaAs/InAlAs symmetric coupled quantum well designed for operations around 1550 nm. Strain balancing was used to allow a thick intrinsic region. Initial versions of this device showed a reduction in drive voltage of about 50%, to 7.5 V, as shown in figure 10. This type of structure is quite sensitive to interface roughness, which increases the exciton linewidths. Newer versions of the symmetric coupled well with optimized growth conditions show narrower exciton linewidths and should allow high contrast modulation at drive voltages below 5 V.

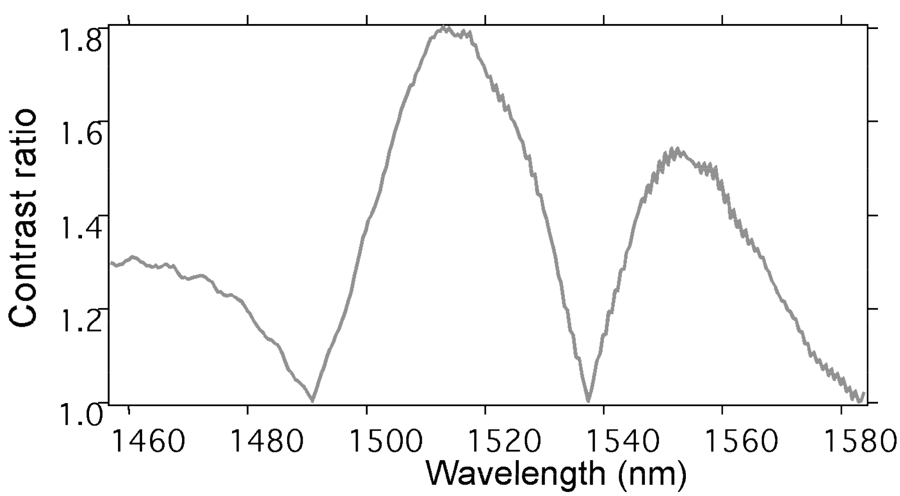

Figure 10. Optical contrast ratio of a coupled quantum well with 7.5 V drive.

4. Alternative modulation formats

The most obvious way to increase the data rate of cat's eye MRR devices is to use small pixels to allow faster modulation. The downside of this approach is that smaller pixels mean more pixels in the MQW focal plane and hence increased complexity in fabrication and electronics. We have described above the use of a cat's eye retroreflector to take advantage of the increased signal to noise that the larger optical aperture of a cat's eye MRR provides. An alternative approach for increasing data rate is to use modulation formats that make more efficient use of the available bandwidth.

Using a cat's eye retro-reflector with a 1 mm diameter MQW modulator, we have demonstrated various vector modulation formats, including phase-shift keying (PSK) and quadrature amplitude modulation (QAM), formats similar to those used in cable modems.

In a QAM signal, there are two carriers, each having the same frequency but differing in phase by 90 degrees. The two modulated carriers are combined at the source for transmission. At the destination, the carriers are separated, the data is extracted from each, and then the data is combined into the original modulating information.

We demonstrated a cat's eye MRR link with various modulation formats including 8PSK, 64QAM, and 256QAM using an Agilent E4431B Signal Generator and an 89441A Vector Signal Analyzer. As shown below in figure 11, an aggregate data rate of 40 Mbits/sec was achieved by using 256QAM with a symbol rate of 5 Msymbols/sec. In this case our symbol rate was limited by the bandwidth of the Agilent signal generator, not the cat's eye MRR. In fact we could have used cat's eye pixels of twice the diameter and still achieved the same data rate. Thus, given adequate signal to noise, a cat's eye MRR using 256 QAM would need only one quarter the number of MQW pixels to produce the same data rate as a system using on off keying. We will investigate these issues further including the effects of modulator linearity and the effects of temperature variation on the modulation transfer function of the MQW.

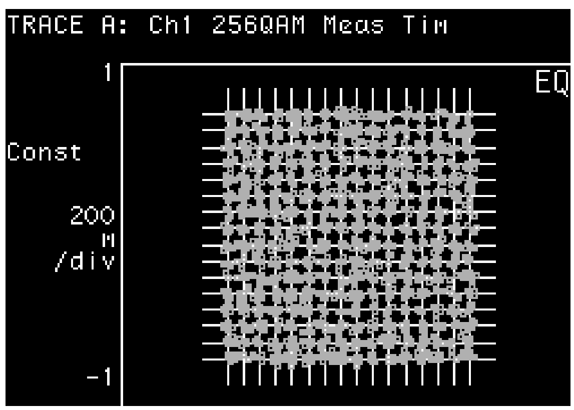

Figure 11. QAM data returned over a modulating retro-reflector link.

5. Conclusion

Cat's eye multiple quantum well modulating retro-reflectors have the potential to increase the maximum data rate of MRR systems by more than an order of magnitude over corner cube systems. This increased data rate comes at a cost of increased optical and in some cases MQW complexity. The form of a cat's eye MRR depends a great deal on how it will be used and what field of view it must cover, but using the right combination of optical and photonic components makes it possible to craft optimal solutions to a variety of problems.

6. Acknowledgements

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